

A new, lower value of total solar irradiance: Evidence and climate significance

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Received 7 October 2010; revised 19 November 2010; accepted 30 November 2010; published 14 January 2011.

[1] The most accurate value of total solar irradiance during the 2008 solar minimum period is $1360.8 \pm 0.5 \text{ W m}^{-2}$ according to measurements from the Total Irradiance Monitor (TIM) on NASA's Solar Radiation and Climate Experiment (SORCE) and a series of new radiometric laboratory tests. This value is significantly lower than the canonical value of $1365.4 \pm 1.3 \text{ W m}^{-2}$ established in the 1990s, which energy balance calculations and climate models currently use. Scattered light is a primary cause of the higher irradiance values measured by the earlier generation of solar radiometers in which the precision aperture defining the measured solar beam is located behind a larger, view-limiting aperture. In the TIM, the opposite order of these apertures precludes this spurious signal by limiting the light entering the instrument. We assess the accuracy and stability of irradiance measurements made since 1978 and the implications of instrument uncertainties and instabilities for climate research in comparison with the new TIM data. TIM's lower solar irradiance value is not a change in the Sun's output, whose variations it detects with stability comparable or superior to prior measurements; instead, its significance is in advancing the capability of monitoring solar irradiance variations on climate-relevant time scales and in improving estimates of Earth energy balance, which the Sun initiates. **Citation:** Kopp, G., and J. L. Lean (2011), A new, lower value of total solar irradiance: Evidence and climate significance, *Geophys. Res. Lett.*, **38**, L01706, doi:10.1029/2010GL045777.

1. The Importance of Total Solar Irradiance for Climate Research

[2] Total solar irradiance (TSI) is Earth's dominant energy input, exceeding the next largest energy source by nearly 10^4 . Even small variations in solar irradiance can produce natural forcing of Earth's climate with global and regional-scale responses [*Intergovernmental Panel on Climate Change (IPCC)*, 2007; *Lean and Rind*, 2009]. Accurate and stable irradiance measurements are therefore critical for establishing the energy balance that determines Earth's climate and for reliable attribution of climate change.

[3] A continuous record of TSI began in 1978 when space-based measurements commenced, providing the database shown in Figure 1a. The construction of a composite irradiance record suitable for climate change applications requires

that measurements made by individual radiometers be adjusted to align their different absolute scales. This is crucial because inaccuracies in individual measurements can be greater than 0.1%, exceeding estimated long-term solar variations. The composite TSI time series in Figure 1b is the average of three such composites, each constructed on its own absolute scale from different combinations of data adjusted in different ways for instrument sensitivity changes during flight [*Willson and Mordvinov*, 2003; *Fröhlich and Lean*, 2004; *Mekaoui and Dewitte*, 2008]. The average composite record in Figure 1b is adjusted to the SORCE/TIM scale, with grey shading indicating the 1σ spread of the average.

[4] The 11-year solar cycle is unequivocal in irradiance measurements made by individual instruments and in the composite time series, according to which monthly averaged TSI values increase approximately 1.6 W m^{-2} (0.12%) between recent solar minima and maxima. Note that the TSI variations during cycles 22 and 23 are similar even though the peak annual mean sunspot number, R_z , a common index of solar activity shown in Figure 1d, was lower during Cycle 23 ($R_z = 119$) than cycle 22 ($R_z = 159$). Rapid solar irradiance variations with larger amplitude are superimposed on the 11-year cycles; decreases on time scales of days to weeks can be as large as 4.6 W m^{-2} (0.34%).

[5] Dark sunspots and bright faculae are the two primary sources of solar irradiance variations. Both are magnetic features that occur in varying number and size on the solar disk, altering the Sun's radiative output affecting the Earth by respectively decreasing and enhancing the local emission. Because the solar activity cycle increases both the dark sunspot and bright facular contributions to TSI, the observed variability is the net effect of these two opposing influences, and thus is not a direct linear function of a single solar activity index such as sunspot number. Shown in Figure 1c is an empirical model [*Lean et al.*, 2005] that combines the separate sunspot and faculae influences (using the *Mg II* index as a proxy for the global facular signal) and accounts for 86% of the variance in the average irradiance composite in Figure 1b.

[6] The characterization of solar irradiance variations afforded by the database, composite time series, and model in Figure 1 has advanced understanding of Sun-climate relationships by facilitating the identification of solar signals in climate records [*Douglass and Clader*, 2002; *Lean and Rind*, 2009], estimates of irradiance changes during the past millennium [*Steinhilber et al.*, 2009], climate model assessments [*Tung et al.*, 2008], and climate change simulations including those used by *IPCC* [2007]. Figure 2 compares the relative roles of natural and anthropogenic climate influences in the past three decades according to empirical analyses of global surface temperatures, using the irradiance variability model in Figure 1c. Taking into account the influences of the El Niño Southern Oscillation (ENSO, at lags of 0, 2, and 10 months),

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Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE NOV 2010		2. REPORT TYPE		3. DATES COVERED 00-00-2010 to 00-00-2010	
4. TITLE AND SUBTITLE A new, lower value of total solar irradiance: Evidence and climate significance				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Research Laboratory,Space Science Division,Washington,DC,20375				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 7	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

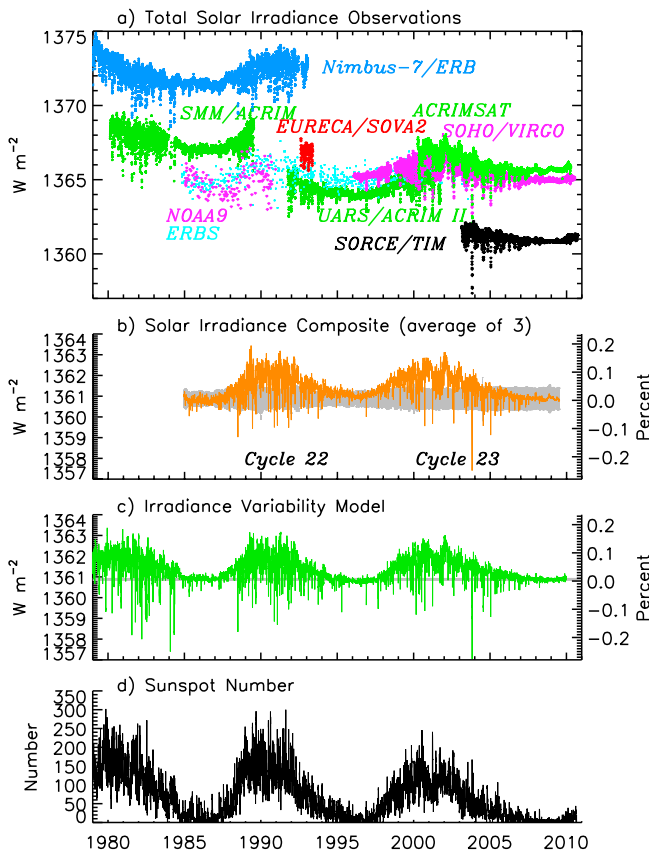


Figure 1. (a) Space-borne total solar irradiance (TSI) measurements are shown on “native” scales with offsets attributable to calibration errors. Instrument overlap allows corrections for offsets and the creation of a composite TSI record. (b) The average of three different reported composites [ACRIM, PMOD, and RMIB] adjusted to match the SORCE/TIM absolute scale. The grey shading indicates the standard deviation of the three composites. (c) Irradiance variations estimated from an empirical model that combines the two primary influences of facular brightening and sunspot darkening with their relative proportions determined via regression from direct observations made by SORCE/TIM. (d) The daily sunspot numbers indicate fluctuating levels of solar activity for the duration of the database.

volcanic aerosols (at lags of 0 and 10 months) and anthropogenic gases, global surface temperature warms $\sim 0.1^\circ\text{C}$ as solar irradiance increases $\sim 0.1\%$ from the minimum to the maximum of recent solar activity cycles [Lean and Rind, 2008, 2009].

[7] On time scales exceeding the 11-year cycle, the Sun’s contribution to global change is controversial [Duffy et al., 2009]. Ambiguities in the TSI record are partly responsible since the TSI record is extrapolated via proxy records of solar activity to extended time ranges for use in climate attribution and sensitivity studies [IPCC, 2007]. Under debate, for example, is whether a purported irradiance increase between cycle minima in 1986 and 1996 [Willson and Mordvinov, 2003] or an irradiance decrease during 2008 [Fröhlich, 2009] indicates secular solar irradiance change in excess of the known sunspot and facular influences. If real, do secular irradiance variations drive significant climate change?

[8] The launch in 2003 of TIM on SORCE commenced a new era of solar irradiance observations with 3 times higher accuracy (0.035%) than prior measurements and with a long-term stability of 0.001% per year [Kopp and Lawrence, 2005; Kopp et al., 2005a]. The TIM reports solar minimum TSI values of $1360.8 \pm 0.5 \text{ W m}^{-2}$, lower by 4.6 W m^{-2} than prior space-borne measurements [Kopp et al., 2005b]. This fundamental difference exceeds prior measurements’ reported uncertainties of $\sim 1.3 \text{ W m}^{-2}$ and exposes an incomplete understanding of space-based solar radiometry [Butler et al., 2008] that compromises the accuracy and long-term stability of the extant TSI record. This paper reports an assessment of current space-based radiometer capabilities based on new laboratory tests to resolve the scale discrepancy and quantify error sources in space-based solar radiometry, and discusses the implications of the indicated new lower TSI value and improved stabilities for climate studies.

2. Space-Based Measurements of Total Solar Irradiance

[9] All TSI instruments employ a common measurement approach, that of active cavity electrical substitution radi-

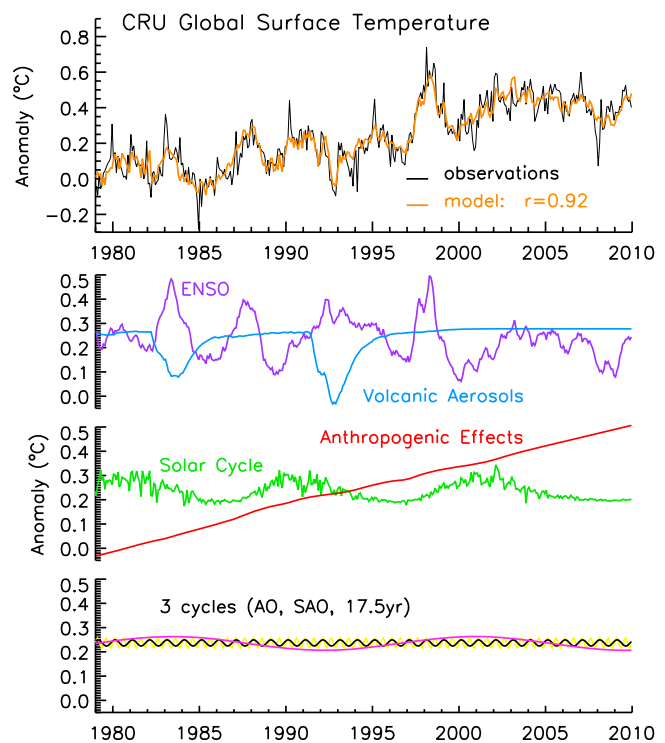


Figure 2. Compared in the top panel are monthly mean variations in the global temperature of the Earth’s surface, from the Climatic Research Unit (CRU, black) and an empirical model (orange, following Lean and Rind [2009]) that combines four primary influences and three minor cycles, whose variations are shown individually in the lower panels. The temperature record has sufficient fidelity that after removing the four primary effects, namely ENSO (purple) at three different lags, volcanic aerosols (blue) at two different lags, solar irradiance (green), and anthropogenic effects (red), minor cycles identifiable as annual (AO, black), semi-annual (SAO, yellow), and 17.5 year oscillations (pink) are evident in the residuals (bottom panel).

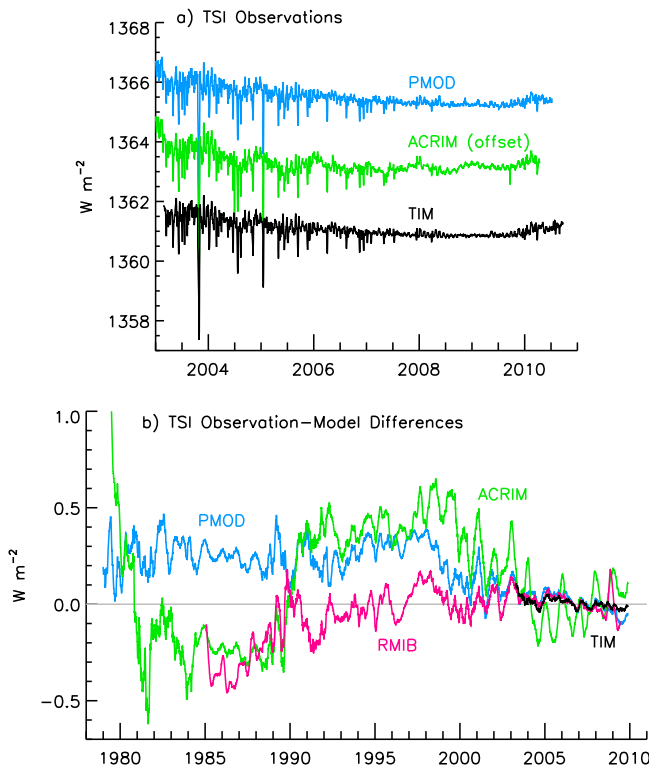


Figure 3. (a) Data from the three on-orbit TSI instruments, the ACRIM III (green), VIRGO (blue), and TIM (black), exhibit generally similar fluctuations, but with notable differences that are not easily attributable to solar variations. (b) Differences between monthly mean reported and modeled irradiance variations for the TIM and three irradiance composites [PMOD, ACRIM, RMIB]. The differences have been smoothed with 81-day running means to expose drifts among the individual composites in comparison with the model, which is based on the combined effects of sunspot and faculae as shown in Figure 1c.

ometry, in which an absorptive blackened cavity is maintained in thermal equilibrium by application of measured electrical heater power while incident radiant solar power passing through a defining precision aperture of calibrated area is modulated via a shutter [Butler *et al.*, 2008]. Once on orbit, radiometric calibrations drift for multiple reasons including solar degradation of the absorptive cavity's interior surfaces, electronic degradation affecting the measured heater power, surface degradation of the precision aperture, and varying surface emissivities and temperatures that alter instrument thermal backgrounds. Instruments utilize various approaches to minimize and quantify known sources of on-orbit instabilities.

2.1. The 32-Year Space-Based Record

[10] The space-based TSI record comprises measurements from more than ten radiometers spanning three solar activity cycles. As Figure 1a illustrates, the SORCE/TIM TSI values are lower than prior measurements made by the Earth Radiometer Budget Experiment (ERBE) on the Earth Radiation Budget Satellite (ERBS) [Lee *et al.*, 1995], VIRGO on the Solar Heliospheric Observatory (SoHO) [Fröhlich and Lean, 2004; Fröhlich, 2009], and the ACRIM

instruments on the Solar Maximum Mission (SMM), Upper Atmosphere Research Satellite (UARS), and ACRIMSat [Willson and Mordvinov, 2003]. Ground calibrations of these flight radiometers relied on component rather than system level measurements since irradiance standards prior to their launches lacked desired absolute accuracies.

[11] Because uncertainties of individual irradiance observations exceed solar irradiance variations ($\sim 0.1\%$), instrument stability and measurement continuity are relied upon to discern real solar irradiance variations in the database. Instrument stability is achieved primarily by exposing redundant radiometer cavities to different accumulations of solar radiation to quantify exposure-dependent degradation effects that are then corrected in reported solar signals. Overlap of sequential radiometer observations permits corrections for absolute offsets and, if sufficiently long, validation of instrumental drifts.

[12] Although ACRIM I, ACRIM II, ACRIM III, VIRGO, and TIM all track degradation with redundant cavities, notable and unexplained differences are evident in Figure 3a among their reported irradiance variations and in Figure 3b with the modeled influences of sunspots and faculae (shown in Figure 1c and used to estimate climate responses in Figure 2). Features not easily attributable to solar activity include an annual cycle that is nearly in phase with the Sun-Earth distance in ACRIM III data, and 90-day spikes in the VIRGO data coincident with SoHO spacecraft maneuvers that are most apparent during the 2008 solar minimum. Disagreement among overlapping observations, as apparent in Figure 3, indicates undetected drifts that suggest the TSI record is not sufficiently stable to discern solar changes on decadal time scales. For example, Figure 3b shows that only the ACRIM composite shows irradiance increasing by $\sim 1 \text{ W m}^{-2}$ between 1986 and 1996; if real, the solar origins of this increase are ambiguous since it is also absent in the model.

[13] The sunspot and faculae model accounts for 92% of the irradiance variance that TIM observes. The correlation of TIM observations and the model is 0.96 (for 2481 daily mean values from 2003 to 2009), the 1σ standard deviation of their differences is 0.09 W m^{-2} , and the trend in the differences is -0.009 W m^{-2} (-0.00066%) per year, well within the TIM stability. The differing and lower correlations between the model and each of the three irradiance composites (0.91 for PMOD, 0.81 for ACRIM, and 0.92 for RMIB) over their entire records suggest the presence of variations in these composite time series, as apparent in Figure 3b, that cannot be explained by our current understanding of the sunspot and facular influences on total solar irradiance.

2.2. Resolving Instrumental Differences

[14] Specific technological advances designed to improve measurement accuracy and stability distinguish the TIM from prior space-based radiometers. These include the forward placement of the defining aperture relative to the view-limiting aperture (rather than the inverse) to reduce stray light (see Figure 4a), phase-sensitive (rather than time domain) signal detection to reduce sensitivity to thermal drifts and signals not in phase with the shuttered sunlight, and etched metal black (instead of painted) cavity interiors to minimize degradation from solar exposure. The TIM also employs a digital signal processor controlled servo system with feed forward that anticipates radiometer heater changes

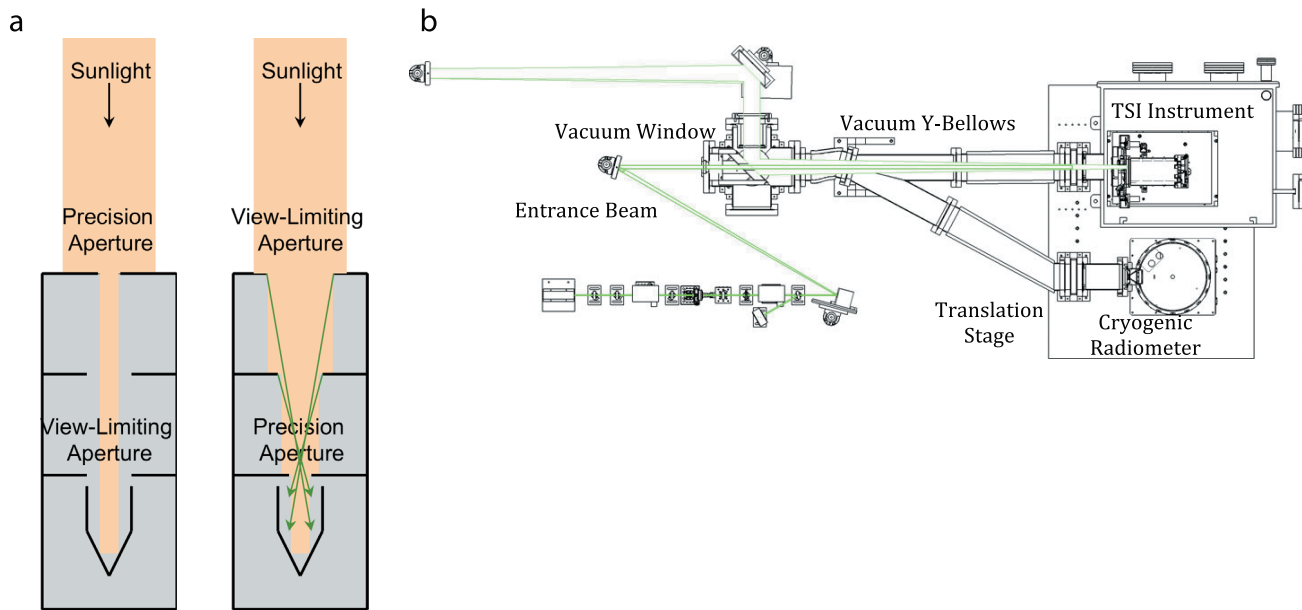


Figure 4. (a) The TIM optical layout places the small precision aperture at the front of the instrument so that only light intended to be measured enters (left-hand figure). All other flight TSI radiometers use the optical layout shown in the right-hand figure, allowing excess light into the instrument interior that can lead to erroneously high irradiance measurements from scatter (indicated in green). (b) A top-view cross-section of the TSI Radiometer Facility (TRF) shows the intensity-stabilized and spatially uniform beam (green beam starting in lower left) entering a vacuum window (left) then following one arm of a flexible vacuum Y-bellows into a TSI instrument (top right). Without breaking vacuum or altering the beam, a linear translation stage (right) can move the TSI instrument out of the beam and position the TRF's NIST-calibrated reference cryogenic radiometer (bottom right) in the same portion of the beam to allow irradiance measurement comparisons.

to nearly eliminate thermal fluctuations as sunlight is modulated [Kopp and Lawrence, 2005]. Furthermore, only the TIM acquires multiple daily measurements of dark ($\sim 4\text{K}$) space to directly determine and correct for instrument thermal background signals.

[15] To better understand the causes of instrument offsets, NIST and NASA hosted a workshop in 2005 to discuss instrument uncertainties and stabilities in detail. Recommendations to resolve the instrument discrepancies [Butler *et al.*, 2008] include: validating optical power measurement accuracy by comparing ground-based versions of the instruments to laboratory references, such as those at NIST; NIST validation of aperture area calibrations using flight spare apertures from each instrument; and applying corrections for diffraction from the view-limiting aperture (a sizeable correction not applied by all instruments).

[16] Notably, for the ACRIM instrument NIST determined that diffraction from the view-limiting aperture contributes a 0.13% signal not accounted for in data from the three ACRIM instruments [Butler *et al.*, 2008]. This correction lowers the reported ACRIM values, resolving part of ACRIM's difference with TIM. In ACRIM and all other instruments, the precision aperture used to define the measured solar beam is deep inside the instrument with a larger view-limiting aperture at the front, which, depending on edge imperfections, in addition to diffraction can directly scatter light into the absorbing cavity. Additionally, this design allows into the instrument interior two to three times the amount of light intended to be measured; if not completely absorbed or scattered back out, this additional light produces erroneously high signals. In contrast, the TIM's

optical design places the precision aperture at the front so only light intended to be measured enters (Figure 4a).

3. Laboratory Characterizations of Solar Radiometers

[17] In pursuing the capability to measure variations in solar irradiance on long time scales without reliance on measurement continuity, the TIM approach of high absolute accuracy establishes a new paradigm for measuring climate variables. Uncertainties of $\sim 0.1\%$, typical of earlier instruments, are inadequate for this task; benchmark measurements with uncertainties $< 0.01\%$ are required [Ohring, 2007], as shown in Figure 5 and discussed in Section 4.

[18] Prior system-level instrument validations compared TSI instruments operating in air while observing through the Earth's atmosphere to the World Radiation Reference, which achieves 0.14–0.3% (2σ) uncertainty [Finsterle *et al.*, 2008]. The needed 10x lower uncertainties require laboratory cryogenic radiometers, vacuum operations, and controlled light sources. For this purpose LASP designed and built the TSI Radiometer Facility (TRF) [Kopp *et al.*, 2007]. Completed in 2008 and based on a reference NIST-calibrated high-power cryogenic radiometer, the TRF is currently the only facility in the world approaching the desired accuracy for pre-launch validation of solar radiometers measuring irradiance (rather than merely optical power) at solar power levels and under vacuum conditions.

[19] At the core of the TSI Radiometer Facility, shown schematically in Figure 4b, is a custom high-power cryogenic radiometer built by L-1 Standards and Technology, Inc. and calibrated for optical power against the NIST Pri-

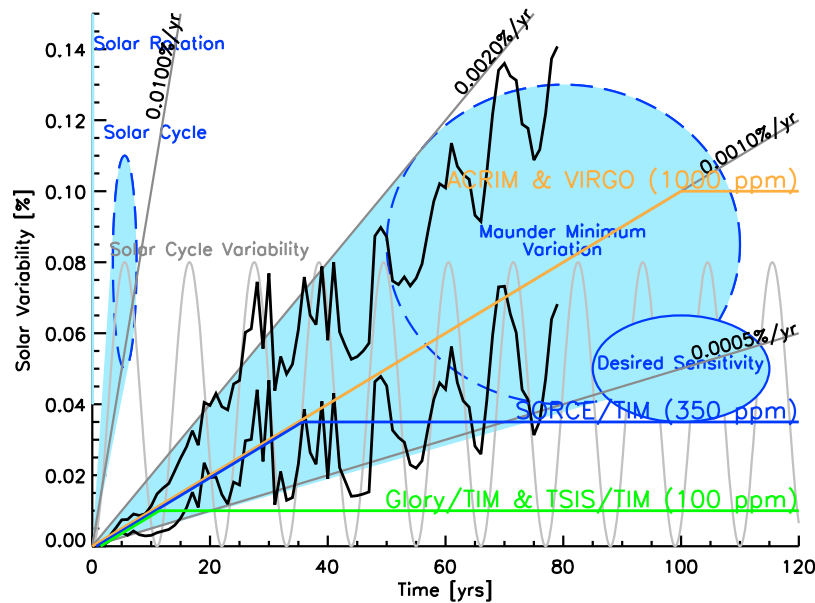


Figure 5. Measured TSI variability levels can exceed 0.3% over solar rotation time scales of 27 days and are typically $\sim 0.1\%$ over the 11-year solar cycle shown in light grey, as indicated by the pale blue ovals for these two time ranges. Two black time series, based on various historical reconstructions (discussed by *Lean et al.* [2005]), bracket the estimated TSI variations as the Sun exited Maunder Minimum. These long-term variations are estimated to be from 0.05 to 0.13% over the ~ 80 years (equivalently 0.0006 to 0.0016%/year) exiting Maunder Minimum, as depicted by the large blue oval. Directly detecting such long-term changes requires 1) instrument stabilities $< 0.001\%$ /year and measurement continuity, and/or 2) measurements having absolute accuracy uncertainties $< 0.01\%$, as intended for the Glory/TIM and TSIS/TIM instruments, so that measurements separated by several decades could detect secular changes. Colored lines representing the stabilities and accuracies of the flight ACRIMs (orange), VIRGO (orange), SORCE/TIM (blue), Glory/TIM (green), and TSIS/TIM (green) delimit the variability levels and time ranges above which each instrument could detect actual solar changes. Current instrument stability levels could marginally detect the estimated TSI variations exiting Maunder Minimum given measurement continuity; improved instrument accuracies enable such detection over decadal time scales even without continuity.

mary Optical Watt Radiometer, a cryogenic radiometer that maintains the NIST radiant power scale to an uncertainty of 0.02% (1σ) [*Houston and Rice*, 2006]. The TRF encloses both the cryogenic radiometer and the TSI instrument under test in a common vacuum system that contains a stationary, spatially uniform illuminating beam. A precision aperture with area calibrated to 0.0031% (1σ) determines the portion of the beam measured by the cryogenic radiometer. By precisely translating the TSI instrument such that its precision aperture is positioned in the same location without optically altering the beam, the instrument's irradiance measurement is directly compared to that of the TRF. Variable beam power provides linearity diagnostics, and variable beam diameter diagnoses scattering from different instrument components.

[20] Calibrations, validations, and diagnostic testing to help resolve measurement differences have been performed at the TRF. The Glory/TIM and PICARD/PREMOS flight instrument absolute scales are now traceable to the TRF in both optical power and irradiance. The high level of accuracy to which this SI traceability is achieved reduces the consequences of a gap in the solar irradiance record in the event that future on-orbit measurement overlap is precluded. Table 1 summarizes results of TRF irradiance measurement comparisons completed for the Glory/TIM and PICARD/PREMOS flight instruments and ground-based versions of the SORCE/TIM and SoHO/VIRGO instruments. Preliminary

tests with a ground-based ACRIM have also been completed.

[21] The Glory/TIM flight instrument channels are lower than the SI-traceable TRF irradiance reference scale by an average of $0.012 \pm 0.020\%$, while the SORCE/TIM ground unit is lower by $0.037 \pm 0.032\%$, consistent with the stated accuracy of the SORCE/TIM flight measurements. The PREMOS-3 flight instrument and the VIRGO-2 ground unit measure irradiances $0.605 \pm 0.027\%$ and $0.743 \pm 0.025\%$ higher than the TRF, respectively, with the discrepancies primarily due to large (0.631% and 0.730%, respectively), poorly understood optical power measurement offsets in these instruments. The ground-based PREMOS-1 is free of this large optical power measurement discrepancy, but lower than the TRF in irradiance by $0.104 \pm 0.038\%$.

[22] TRF tests indicate that unaccounted-for scattering and diffraction in non-TIM instruments produce erroneously high irradiance values and likely cause the majority of the offsets in the TSI data record in Figure 1a. By underfilling then overfilling an instrument's view-limiting aperture with the TRF beam it is possible to diagnose the effects of diffraction and scatter from that entrance aperture. Although the PREMOS and VIRGO instruments implement a diffraction correction (calculated analytically), scatter is material- and surface-dependent and must be measured. The scatter effects measured by the TRF produce spurious signal increases of 0.10% for PREMOS-1, 0.04% for PREMOS-3,

Table 1. Difference Relative to TSI Radiometer Facility^a

Instrument	Irradiance: View-Limiting Aperture Overfilled	Irradiance: Precision Aperture Overfilled	Difference Attributable To Scatter Error	Measured Optical Power Error	Residual Irradiance Agreement	Uncertainty
SORCE/TIM <i>ground</i>	NA	−0.037%	NA	−0.037%	0.000%	0.032%
Glory/TIM <i>flight</i>	NA	−0.012%	NA	−0.029%	0.017%	0.020%
PREMOS-1 <i>ground</i>	−0.005%	−0.104%	0.098%	−0.049%	−0.104%	~0.038%
PREMOS-3 <i>flight</i>	0.642%	0.605%	0.037%	0.631%	−0.026%	~0.027%
VIRGO-2 <i>ground</i>	0.897%	0.743%	0.154%	0.730%	0.013%	~0.025%

^aIrradiance calibration comparisons of solar radiometers are given as relative differences from the reference TRF measurement. The Glory/TIM flight instrument and ground-based SORCE/TIM instrument validations agree within the comparison uncertainties when measuring irradiances of a spatially extended beam; however uncorrected scatter in the PREMOS-1 (ground-based), PREMOS-3 (a PICARD flight TSI instrument), and the VIRGO-2 radiometer (representative of SoHO/VIRGO flight instrument) in addition to an optical power offset affecting PREMOS-3 and VIRGO-2 leads to erroneously high readings in these instruments. These effects will likely be corrected in PREMOS flight results, but are not currently accounted for in released VIRGO data.

and 0.15% for VIRGO-2 (see Table 1). These monochromatic measurements do not provide true solar scatter corrections, but they indicate scatter contributes a sizeable fraction of the amount by which flight radiometers with this aperture layout measure irradiance values higher than SORCE/TIM.

4. Consequences of Solar Irradiance Measurements for Climate Research

4.1. Accuracy

[23] Instrument inaccuracies are a significant source of uncertainty in determining Earth's energy balance from space-based measurements of incoming and reflected solar radiation and outgoing terrestrial thermal radiation. A non-zero average global net radiation at the top of the atmosphere is indicative of Earth's thermal disequilibrium imposed by climate forcing. But whereas the current planetary imbalance is nominally 0.85 W m^{-2} [Hansen *et al.*, 2005], estimates of this quantity from space-based measurements range from 3 to 7 W m^{-2} . SORCE/TIM's lower TSI value reduces this discrepancy by 1 W m^{-2} [Loeb *et al.*, 2009]. We note that the difference between the new lower TIM value with earlier TSI measurements corresponds to an equivalent climate forcing of -0.8 W m^{-2} , which is comparable to the current energy imbalance.

[24] The impact of the new low TSI value on climate models is unknown. A few tenths percent change in the absolute TSI level is typically considered to be of minimal consequence for climate simulations. However, model parameters are adjusted to ensure adequate representation of current climate, for which incoming solar radiation is a decisive factor. Underway are experiments with the GISS Model 3 to investigate the sensitivity of model performance to the TSI absolute value during present and pre-industrial epochs, and describe, for example, how the irradiance reduction is partitioned between the atmosphere and surface and the effects on outgoing radiation.

[25] Improved measurement accuracy from SI-traceable standards is a key requisite for all future climate records, including solar irradiance [National Research Council, 2007; Ohring, 2007]. Because climate records must be acquired over many decades, measurement accuracy adequate to detect the expected variations independently of continuity makes the records less susceptible to loss in the event of a data gap. Furthermore, as Sections 2 and 3

demonstrate, measurement inaccuracies from incomplete instrument characterizations cause liabilities in climate records. Accuracy uncertainties of $<0.01\%$ are required to detect long term solar irradiance variations surmised to underlie the activity cycle because expected changes are in the range 0.05 to 0.15 W m^{-2} per century [Lean *et al.*, 2005]. Figure 5 illustrates the relationship between postulated secular irradiance variations and the needed accuracy and stability of TSI measurements to detect such changes.

4.2. Stability

[26] Because a change in solar irradiance imparts a direct radiative climate forcing, drifts in solar radiometers that are mistaken for true solar irradiance variations can be misinterpreted as causing natural-driven climate change. Examples include the much-debated issue of the irradiance increase between cycle minima in 1986 and 1996, evident in the ACRIM composite (but lacking in other composites and the model) and the low irradiance levels in the PMOD composite during the 2008 minimum. Substantiating the detection of long-term irradiance impacts on climate requires stability that surpasses that of the current total irradiance record.

[27] A stable record of solar irradiance variations combined with reliable global surface temperature observations can provide a tool for quantifying climate response processes to radiative forcing on decadal time scales. The association of the observed 0.1% irradiance solar cycle increase (Figure 1) imparts 0.22 W m^{-2} instantaneous climate forcing, for which the empirically detected global temperature increase of 0.1°C (Figure 2) suggests a transient climate response of $0.6^\circ\text{C per W m}^{-2}$ [Douglass and Clader, 2002]. This response is larger by a factor of 2 or more than in the current models assessed by IPCC [Tung *et al.*, 2008], possibly because of the models' excessive heat uptake by the ocean. With a stable multi-decadal solar irradiance record, it will be possible to quantify the relationship between transient and (likely larger) equilibrium responses.

5. Summary

[28] The most probable value of total solar irradiance representative of solar minimum is $1360.8 \pm 0.5 \text{ W m}^{-2}$, lower than the canonical value of $1365.4 \pm 1.3 \text{ W m}^{-2}$ recommended a decade ago. This new value, measured by SORCE/TIM, is validated by irradiance comparisons to a

NIST-calibrated cryogenic radiometer in the new TSI Radiometer Facility. Uncorrected scattering and diffraction are shown to cause erroneously high readings in non-TIM instruments.

[29] In addition to the offsets, published irradiance observations composing the 32-year TSI database lack coherent temporal structure because of inconsistent trends that indicate the presence of uncorrected instrumental drift and are not explained by known sources of solar irradiance variability. A regression model that determines the relative proportion of sunspot and facular influences directly from the SORCE/TIM data accounts for 92% of observed variance and tracks the observed trends to within TIM's stability. This close agreement provides further evidence that TSI variations are primarily due to surface magnetic activity. Uncorrected instrumental drifts are the likely reason that none of the irradiance composites show consistency in their trends nor achieve the high level of agreement with the model as the TIM does.

[30] Climate change studies that use published TSI time series to accredit solar responses must be cognizant of the possible errors in the record; otherwise climate variability is incorrectly attributed to solar variations that are in fact instrumental drifts. The current database is too short and imprecise to establish the magnitude of long-term irradiance changes, or to alleviate conflicting claims of irradiance variations driving significant climate change in recent decades. Achieving 0.01% uncertainties with stabilities <0.001% per year (the future TIM instrument measurement goals) will help discern secular changes in solar irradiance, making the 32-year TSI climate data record more robust against potential measurement gaps and more reliable for climate change applications.

[31] As the Sun imparts the only significant long-term external forcing of climate, an accurate and stable record of solar irradiance variations is essential for climate change attribution, and provides a unique tool for investigating climate sensitivity with theoretical and empirical models; but only when instrumental effects are unequivocally quantified in (and removed from) the irradiance database will it be possible to construct irradiance records with the accuracy and precision needed for these tasks. The results reported herein, along with continued measurement community efforts to validate instrument error budgets through end-to-end laboratory testing, are the first steps toward achieving these goals.

[32] **Acknowledgments.** NASA Earth Sciences supported this work under the SORCE and Glory programs. Discussions with the SORCE and Glory TIM teams and with David Rind are gratefully acknowledged, as are thoughtful comments from Peter Pilewskie's, Wolfgang Finsterle's, and an unidentified reviewer's careful reading of the paper.

References

- Butler, J., B. C. Johnson, J. P. Rice, E. L. Shirley, and R. A. Barnes (2008), Sources of differences in on-orbital total solar irradiance measurements and description of a proposed laboratory intercomparison, *J. Res. Natl. Inst. Stand. Technol.*, **113**, 187–203.
- Douglass, D. H., and B. D. Clader (2002), Climate sensitivity of the Earth to solar irradiance, *Geophys. Res. Lett.*, **29**(16), 1786, doi:10.1029/2002GL015345.
- Duffy, P. B., B. D. Santer, and T. M. Wigley (2009), Solar variability does not explain late-20th-century warming, *Phys. Today*, **62**, 48–49, doi:10.1063/1.3074263.
- Finsterle, W., et al. (2008), Third comparison of the World Radiometric Reference and the SI radiometric scale, *Metrologia*, **45**, 377–381, doi:10.1088/0026-1394/45/4/001.
- Fröhlich, C. (2009), Evidence of a long-term trend in total solar irradiance, *Astron. Astrophys.*, **501**, L27–L30, doi:10.1051/0004-6361/200912318.
- Fröhlich, C., and J. Lean (2004), Solar radiative output and its variability: Evidence and Mechanisms, *Astron. Astrophys. Rev.*, **12**(4), 273–320, doi:10.1007/s00159-004-0024-1.
- Hansen, J. E., et al. (2005), Earth's energy imbalance: Confirmation and implications, *Science*, **308**, 1431–1435, doi:10.1126/science.1110252.
- Houston, J. M., and J. P. Rice (2006), NIST reference cryogenic radiometer designed for versatile performance, *Metrologia*, **43**, S31–S35, doi:10.1088/0026-1394/43/2/S07.
- Intergovernmental Panel on Climate Change (IPCC) (2007), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., Cambridge Univ. Press, Cambridge, U. K.
- Kopp, G., and G. Lawrence (2005), The Total Irradiance Monitor (TIM): Instrument design, *Sol. Phys.*, **230**, 1–2, doi:10.1007/s11207-005-7446-4.
- Kopp, G., K. Heuerman, and G. Lawrence (2005a), The Total Irradiance Monitor (TIM): Instrument Calibration, *Sol. Phys.*, **230**, 111–127, doi:10.1007/s11207-005-7447-3.
- Kopp, G., G. Lawrence, and G. Rottman (2005b), The Total Irradiance Monitor (TIM): Science results, *Sol. Phys.*, **230**, 129–139, doi:10.1007/s11207-005-7433-9.
- Kopp, G., K. Heuerman, D. Harber, and V. Drake (2007), The TSI Radiometer Facility: Absolute calibrations for total solar irradiance instruments, *Proc. SPIE*, **6677**, 667709, doi:10.1117/12.734553.
- Lean, J. L., and D. H. Rind (2008), How natural and anthropogenic influences alter global and regional surface temperatures: 1889 to 2006, *Geophys. Res. Lett.*, **35**, L18701, doi:10.1029/2008GL034864.
- Lean, J. L., and D. H. Rind (2009), How will Earth's surface temperature change in future decades?, *Geophys. Res. Lett.*, **36**, L15708, doi:10.1029/2009GL038932.
- Lean, J., G. Rottman, J. Harder, and G. Kopp (2005), SORCE contributions to new understanding of global change and solar variability, *Sol. Phys.*, **230**, 27–53, doi:10.1007/s11207-005-1527-2.
- Lee, R. B., III, M. A. Gibson, R. S. Wilson, and S. Thomas (1995), Long-term total solar irradiance variability during sunspot cycle 22, *J. Geophys. Res.*, **100**, 1667–1675, doi:10.1029/94JA02897.
- Loeb, N. G., B. A. Wielicki, D. R. Doelling, G. L. Smith, D. F. Keyes, S. Kato, N. Manalo-Smith, and T. Wong (2009), Toward optimal closure of the Earth's top-of-atmosphere radiation budget, *J. Clim.*, **22**, 748–766, doi:10.1175/2008JCLI2637.1.
- Mekaoui, S., and S. Dewitte (2008), Total Solar Irradiance measurement and modeling during cycle 23, *Sol. Phys.*, **247**, 203–216, doi:10.1007/s11207-007-9070-y.
- National Research Council (2007), *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*, Natl. Acad. Press, Washington, D. C.
- Ohring, G. (Ed.) (2007), *Achieving Satellite Instrument Calibration for Climate Change (ASIC3)*, NOAA, Silver Spring, Md.
- Steinhilber, F., J. Beer, and C. Fröhlich (2009), Total solar irradiance during the Holocene, *Geophys. Res. Lett.*, **36**, L19704, doi:10.1029/2009GL040142.
- Tung, K. K., J. Zhou, and C. D. Camp (2008), Constraining model transient climate response using independent observations of solar-cycle forcing and response, *Geophys. Res. Lett.*, **35**, L17707, doi:10.1029/2008GL034240.
- Willson, R. C., and A. V. Mordvinov (2003), Secular total solar irradiance trend during solar cycles 21–23, *Geophys. Res. Lett.*, **30**(5), 1199, doi:10.1029/2002GL016038.
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